AD-A060 804 AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA) F/G 11/6

ACTUAL AND PREDICTED FATIGUE LIVES OF D6AC STEEL IN VERY DRY AN--ETC(U)

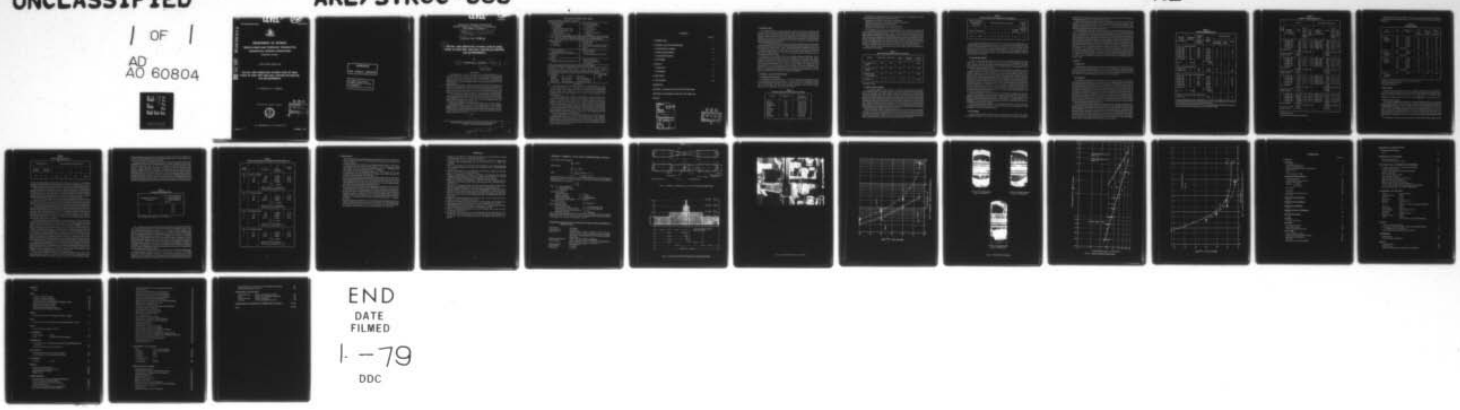
OCT 77 J Y MANN, D S KEMSLEY

UNCLASSIFIED ARL/STRUC-388 NL

1 OF 1

AD

A0 60804



END

DATE

FILMED

1-79

DDC

LEVEL

ARL-Struc-Report-366

AR-000-857

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

STRUCTURES REPORT 366

ACTUAL AND PREDICTED FATIGUE LIVES OF D6AC STEEL IN VERY DRY AND FULLY WATER SATURATED AIR ENVIRONMENTS

J. Y. MANN and D. S. KEMSLEY

Approved for Public Release.

COPY No 18

OCTOBER, 1977

LEVEL

AR-000-857

AERONAUTICAL RESEARCH LABORATORIES
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
DEPARTMENT OF DEFENCE

(14) ARL/STRUC-388

(9) STRUCTURES REPORT, 366

(6)

ACTUAL AND PREDICTED FATIGUE LIVES OF D6AC STEEL IN VERY DRY AND FULLY WATER SATURATED AIR ENVIRONMENTS,

by

(10) J. Y. MANN and D. S. KEMSLEY (11) Oct 77

(12) 29p.

SUMMARY

Axial load fatigue tests have been carried out on keyhole-notched ($K_t = 3 \cdot 1$) *specimens of D6AC steel (UTS = 1,600 MPa) in very dry air and in air fully saturated with water vapour. These included tests under constant-amplitude and four-load-range program loading in both environments. Estimates were made of crack initiation and propagation lives, and crack propagation rates, from the 'program markings' on the fracture surfaces.*

Under the four-load-range (standard) program loading sequence used in this investigation, the total *fatigue lives in a fully water-saturated air environment were about 35% of those in very dry air. Other tests in which the two highest-load-range cycles in each program of 2594 cycles in the sequence were omitted (truncation) reduced the* total *fatigue lives by about 40% and 50% respectively in the wet and dry air environments.*

In wet air the crack initiation life under the standard program was about half that in dry air, and the propagation life to failure about one-third of that in dry air. The average crack propagation rate in wet air was up to three times faster than that in dry air. This indicates that the environment has a greater effect on the crack propagation phase than on the crack initiation phase of the fatigue process.

Fatigue life predictions for the programmed loading cases were made using the constant-amplitude fatigue data and the simple Palmgren–Miner linear cumulative damage hypothesis. For both environments, the predicted program lives were less than the actual lives, the ratio predicted/actual being about 0·36 under dry air and about 0·33 under wet air conditions. Thus, under the particular sequence of loads and environments used, the predictive method was conservative.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

008650

LB

DOCUMENT CONTROL DATA SHEET

Security classification of this page: Unclassified

1. Document Numbers: (a) AR Number: AR-000-857 (b) Document Series and Number: ARL Structures Report—366 (c) Report Number: ARL/Struc.—Rept.—366	2. Security Classification: (a) Complete Document: Unclassified (b) Titile in Isolation: Unclassified (c) Summary in Isolation: Unclassified
3. Title: ACTUAL AND PREDICTED FATIGUE LIVES OF D6AC STEEL IN VERY DRY AND FULLY WATER SATURATED AIR ENVIRONMENTS	
4. Personal Authors: J. Y. Mann, D. S. Kemsley	5. Document Date: October, 1977 6. Type of Report and Period Covered: Report
7. Corporate Author(s): Aeronautical Research Laboratories	8. Reference Numbers: (a) Task: RD. 73 (b) Sponsoring Agency: DST 76/155
9. Cost Code: 257021	
10. Imprint: Aeronautical Research Laboratories, 1977	11. Computer Programs: (Title(s) and language(s)): Not Applicable

12. Release Limitations (of the document): Approved for Public Release

12-0. Overseas:	No.		P.R.	1	A		B		C		D		E	

13. Announcement Limitations (of the information on this page): No Limitation

14. Descriptors:				15. Cosati Codes:
Fatigue life	Air	Steels	D6AC Steel	2012
Humidity	Moisture content		Fatigue (Materials)	1113
Water vapour	Environments		Corrosion environments	
Fatigue tests	Crack propagation		Cracking (Fracturing)	

16. *ABSTRACT*

Axial load fatigue tests have been carried out on keyhole-notched ($K_t = 3 \cdot 1$) specimens of D6AC steel (UTS = 1,600 MPa) in very dry air and in air fully saturated with water vapour. These included tests under constant-amplitude and four-load-range program loading in both environments. Estimates were made of crack initiation and propagation lives, and crack propagation rates, from the 'program markings' on the fracture surfaces.

Under the four-load-range (standard) program loading sequence used in this investigation, the total fatigue lives in a fully water-saturated air environment were about 35% of those in very dry air. Other tests in which the two highest-load-range cycles in each program of 2594 cycles in the sequence were omitted (truncation) reduced the total fatigue lives by about 40% and 50% respectively in the wet and dry air environments.

In wet air the crack initiation life under the standard program was about half that in dry air, and the propagation life to failure about one-third of that in dry air. The average crack propagation rate in wet air was up to three times faster than that in dry air. This indicates that the environment has a greater effect on the crack propagation phase than on the crack initiation phase of the fatigue process.

Fatigue life predictions for the programmed loading cases were made using the constant-amplitude fatigue data and the simple Palmgren–Miner linear cumulative damage hypothesis. For both environments, the predicted program lives were less than the actual lives, the ratio predicted/actual being about 0·36 under dry air and about 0·33 under wet air conditions. Thus, under the particular sequence of loads and environments used, the predictive method was conservative.

CONTENTS

1. INTRODUCTION

A considerable amount of research has been carried out on materials, components and structures to assess the effects of multi-load-level histories on fatigue life. Most of this work has been done under 'normal' laboratory conditions in which wide variations in temperature and humidity would not usually be expected. In subsequent service-life estimates made using such fatigue data, it is not common to consider the extremes of the environment to which the product may be subjected during its operational life or to assess how variations in such conditions may influence the predicted and actual lives.

It is now well established, however, that in an environment of air saturated with water vapour, fatigue crack propagation rates can be much faster and the total fatigue lives much less than in an unsaturated air environment (Refs 1 and 2). Although intermediate humidities have been used by a number of investigators (for example see Refs 3 and 4) there has been little attention given to comparing fatigue behaviour under multi-load-level fatigue loading sequences in the two extreme environmental conditions—very dry air containing virtually no water vapour, and air fully saturated with water vapour.

Previous work by the authors (Ref. 5) on ultra-high-strength SAE 4340 steel using a four-load-range program load sequence, indicated a difference in average fatigue life by a factor of about five for specimens tested in the very dry and fully water saturated air environments respectively. This work has now been extended to include D6AC steel, and has been supported with constant-amplitude fatigue tests at each of the four different load ranges used in the program-load tests so that comparisons could be made of the actual and predicted lives under the two extreme environmental conditions. This report presents the findings of the first phase of an investigation into the influence of water-containing air environments on the fatigue behaviour of D6AC steel heat treated to an ultra-high-strength level.

2. MATERIAL AND TEST PROCEDURES

2.1 Material and Test Specimens

The key-hole notched specimens of $K_t = 3 \cdot 15$ (Fig. 1) used in this investigation were taken in the longitudinal direction from three bars of a batch of 90 mm $\times$ 25 mm D6AC steel bar (Laboratory designation EM) manufactured in accordance with the U.S. Specification A.M.S. 6431, issue of 30 June 1964. The average chemical composition of this batch of material, together with the Specification ranges, are given in Table 1.

TABLE 1
Chemical Composition of D6AC Steel Test Material

Element	Test Material (%)	Specification A.M.S. 6431 (%)
Carbon	0·46	0·45 to 0·50
Manganese	0·78	0·60 to 0·90
Molybdenum	1·25	0·90 to 1·10
Nickel	0·57	0·40 to 0·70
Chromium	1·07	0·90 to 1·20
Vanadium	0·11	0·08 to 0·15
Silicon	0·22	0·15 to 0·30
Sulphur	0·003	0·015 max.
Phosphorus	0·003	0·015 max.

Specimens were rough machined from the normalised bars to approximately 1·25 mm oversize and then heat treated to the following schedule:

Austenitize in salt at 930±5°C for ½ hour at temperature;
Quench into salt at 520±5°C and hold for ½ hour (ausbay quench);
Quench into hot circulating oil at 50°C to 60°C;
Temper in salt bath at 580±5°C for 1 hour, and air cool;
Re-temper in salt bath at 580±5°C for 1 hour and air cool.

Finish machining of the test section included grinding the 14 mm diameter, and fly-cutting (with a carbide-tip tool) the 100 mm radii. After fly-cutting, the two faces of the test section were machine polished longitudinally (under a stream of water) using silicon carbide wet and dry papers finishing with 200 strokes of 600 grit paper. The two circular holes forming the stress concentrator were then drilled with 2·0 mm high speed steel drills and finish reamed with 2·2 mm diameter solid carbide reamers, the connecting slot being produced by spark machining. Finally, the faces were lightly hand polished with 600 grit paper to remove machining burrs at the stress concentrator. Immediately prior to testing, the specimens were cleaned ultrasonically for 10 minutes in a detergent solution, washed in hot water, then in alcohol, and dried in hot air.

Table 2 gives the static tensile properties of the heat-treated material determined using 10 mm diameter test specimens.

TABLE 2
Static Tensile Properties of Heat-treated Material

Property	Minimum	Maximum	Average (*)	Standard deviation	Coeff. of variation
0·1% proof stress (MPa)	1365	1395	1380	10	0·007
0·2% proof stress (MPa)	1390	1420	1415	13	0·009
Ultimate tensile strength (MPa)	1545	1570	1555	10	0·006
Elongation (%)	11·5	12·5	12·0	0·4	0·033

* Average of 6 tests.

2.2 Fatigue Loading Conditions

A Losenhausen UHS20 hydraulic pulsator was used for the fatigue tests. All specimens were mounted vertically in the testing machine and loaded axially under repeated tension. Most of the specimens tested under spectrum loading were subjected to the four-load-range ("standard") program shown in Fig. 2. which contained a total of 2594 cycles per program, and which was derived from a flight load spectrum for a military aircraft. In addition, three program-load tests were made using the same program loading sequence except that the two cycles at the maximum load range were omitted and two additional cycles included at the lowest load range (the "truncated" program). Each test was begun at the lowest load range in the program, and fatigue cycling was continued until complete fracture of the specimen occurred. Constant-amplitude fatigue tests to complete fracture were also made under loading conditions corresponding to each of the four load ranges of the program-load tests.

Under the particular machine control conditions used, the cyclic wave form was triangular (saw-tooth), with a faster rate of unloading per cycle than of loading. In a given test, the *rates* of *loading* and of *unloading* respectively were constant in each of the four load ranges in the program. Consequently, the "frequency of cycling" in each load range depended on the magnitude of the corresponding maximum load, and the relevant details are given in Table 3.

TABLE 3

Rates of Loading and Unloading and Cyclic Frequencies

Rate of loading and unloading in each cycle (MPa/s)		Cyclic frequency (Hz) at load range					Rate of program load application (programs/hour)
loading	unloading	1	2	3	4	average/program	
495	1580	1·1	0·7	0·6	0·5	0·9	1·25

Six specimens were fatigue tested in both the "dry" and "wet" air environments under the standard program loading sequence shown in Fig. 2, and five under constant-amplitude at each of the four load ranges (again in both environments), giving a total of 52 specimens. Of the three program-load tests made using the truncated program, two were done under "dry" air conditions and one under "wet" conditions. Both program and constant-amplitude sequences were continuously recorded during the fatigue tests through strain gauges mounted on one of the loading columns of the pulsator.

2.3 Environmental Conditions

In every case the fatigue specimens were enclosed in an environmental chamber containing either "dry" or "wet" air. The chamber consisted of a horizontal rectangular-section tube 70 mm $\times$ 100 mm $\times$ 500 mm long made of polymethylmethacrylate, which could be separated in the middle for the insertion and removal of the specimen from the testing machine. Fig. 3 illustrates the chamber mounted in position.

"Dry" air conditions were achieved by using commercial "Medical dry breathing air" which contained less than 1 g of water vapour per kg of dry air. This was supplied from a bank of standard compressed air cylinders connected to the environmental chamber through pressure reducing valves and a flow meter by a flexible rubber hose. The flow rate adopted was approximately 2·5 l/min. After passing through a fan-agitated mixing chamber the air passed continually through the notch and around the specimen and then out through an open chimney at the other end of the box. In order to ensure that the test conditions in the environmental chamber could be maintained irrespective of temperature changes in the surrounding laboratory atmosphere the specimen temperature was controlled at 35 ± 1°C by means of a small electrical heating coil around the specimen test section. This coil had widely spaced windings to allow free access of the environment to the stress concentrator. Both the specimen temperature and humidity were continuously monitored throughout the tests. In all "dry" air cases the relative humidity of the air at the test specimen was less than 2%.

Fully water saturated ("wet") air conditions were obtained by bubbling the compressed medical dry breathing air (at the same flow rate) through a 25 mm deep water bath which was situated in the mixing chamber and maintained at a temperature of 46°C. This provided, at the test specimen, air fully saturated with water vapour, i.e. 100% R.H. or condensing conditions, at a temperature of 35°C. The heating coil surrounding the specimen was not electrically connected during tests at the 100% R.H. conditions.

A period of approximately one hour was required after inserting the specimen in the testing machine for the environmental chamber to stabilize either the dry or wet air conditions. No load was applied to the specimens during this period.

2.4 Fractography

After removing the broken specimens from the testing machine, the pieces were cleaned ultrasonically, washed in hot water, then in alcohol and dried in a hot air stream. The specimens

tested in dry air presented a clean uncorroded fracture appearance, but some of the fractures of specimens tested in wet air still exhibited surface corrosion.

Most fracture surfaces were initially examined under low power (up to 30×) in a stereoscopic microscope, while selected specimens—both program-loading and constant-amplitude—were examined in a scanning electron microscope at up to 500×. These included specimens tested under the standard program in both wet and dry air, and one specimen from each constant-amplitude load range/environmental testing condition.

Macrophotographs were taken of the fracture surfaces of all program-loaded specimens, and 20× enlargements used to determine the crack propagation lives and estimate the fatigue lives to crack initiation. This was done by drawing a radial line from what was assumed to be the origin of the longest crack, and then counting back the number of repetitions of an apparently recurring feature which was considered to correspond to the same point in each program. This gave a measure of the number of programs of crack propagation. For specimens tested in dry air it was possible to count back to within an absolute dimension of about 0·1 mm of the origin, whereas for specimens tested in wet air it was not possible to identify positively markings at closer than about 0·7 mm from the origin. However, extrapolation of plots of crack length versus programs for the wet air specimens enabled an estimate to be made—to an accuracy of about one program—of the number of programs at which the crack length was 0·1 mm. Taking 0·1 mm as the datum, the "initiation" life was then obtained as the difference between the total programs to failure and the number of "programs" counted or estimated on the fracture surfaces.

Measurements of the spacing of the program markings enabled an estimate to be made of the extent of crack propagation per program, and hence of the crack propagation rate per *program*, da/dN.

3. RESULTS

3.1 Fatigue Tests

The results of the standard and truncated program load fatigue tests in both the "dry" and "wet" environments are given in Table 4, while the constant-amplitude test results are detailed in Table 5 and shown on the S/N diagram, Fig. 4. The average S/N curves were derived from a least-squares analysis of the data with the assumptions of a log normal distribution of lives and that the S/N curve could be adequately defined by a polynomial function.

3.2 Fractography

Well-defined macroscopic bands were exhibited on the fracture surfaces of all specimens tested under program-loading in dry air. The fractures of the standard-program load specimens were characterised by the presence of narrow dark bands (Fig. 5(a)), which were absent in the specimen tested under the truncated program (Fig. 5(b)). It was therefore assumed that the narrow dark bands were associated with crack propagation under the two cycles per program of the highest load range (Stage 4). However, although crack propagation under Stage 3 loads of the sequence was identifiable on the fracture surfaces of standard program load specimens on both sides of the narrow dark bands, the associated boundaries were too indistinct to permit measurement. In addition, the pattern of bands was not as obvious on the truncated-program specimen fracture surface as on those of specimens tested under the standard-program. Bands were also apparent on the fracture surfaces of all specimens tested in wet air—see, for example, Fig. 5(c). However, they were fewer in number, less clearly defined, and more widely spaced than for the corresponding specimens tested in dry air.

When viewed in the scanning electron microscope, the fracture surfaces of specimens tested at each load range under constant-amplitude conditions in dry air exhibited a flat but somewhat dimpled appearance. With decreasing load range the only obvious difference was that the extent of what appeared to be fissures on the surface became progressively less. Although similar characteristics were apparent for specimens tested in wet air at the three highest load ranges, the fracture surface of the specimen tested at the lowest range was distinguished by the presence of intercrystalline facets. Under program loading, areas of the fracture apparently developed by each of the four load ranges exhibited generally similar appearances to the corresponding fractures under constant-amplitude loading at the same crack length.

TABLE 4
Results of Program-load Tests

Specimen Number (test number)	Completed Programs	Completed Cycles in last (incomplete) Program	Total Cycles to Failure	Failure Condition		
				Ascending Descending	Load Range	Cycles
"Dry" air (standard program)						
55 DC2 (38)	47	1296	123 214	A	4	0
55 DF2 (39)	44	1296	115 432	A	4	0†
55 DA1 (40)	41	1242	107 596	A	3	10
55 EC2 (52)	45	1297	118 027	A	4	1
55 EF2 (53)	52	1297	136 185	A	4	1
15 BG2 (154)	48	1296	125 808	A	4	0
log. average	46·0		120 716 (46·5 prog.)			
log. s.d.	0·0353		0·0350			
"Dry" air (truncated program)						
15 BF4 (153)*	31	1302	81 716	D	3	4
15 BG3 (155)	29	794	76 020	A	2	124
Fully water saturated air (standard program)						
55 EB1 (55)	18	1297	47 989	A	4	1
55 ED1 (56)	16	1257	42 761	A	3	25
55 EE1 (58)	20	1177	53 057	A	2	507
55 DF1 (61)	17	1296	45 394	A	4	0
55 EF1 (84)	15	1270	40 180	A	3	38
15 BD1 (150)	17	1232	45 330	A	3	0
log. average	17·1		45 609 (17·6 prog.)			
log. s.d.	0·0429		0·0415			
Fully water saturated air (truncated program)						
15 BE2 (152)	9	55	23 401	A	1	55

* Truncated program in this test contained two cycles more in Load Range 3 and two cycles less in Load Range 1 than in the other truncated program tests.

† Zero in this column indicates failure at a load level greater than the maximum of the previous load range, but less than the maximum of the load range at failure.

TABLE 5

Results of Constant-amplitude Tests

	Dry Air				Fully Water Saturated Air			
Load range	Specimen Number (Test number)	Cycles	Average Cyclic Frequency (Hz)	Testing Time (hrs)	Specimen Number (Test number)	Cycles	Average Cyclic Frequency (Hz)	Testing Time (hrs)
4	55 DB1 (63)†	3376	0·44	2·23	15 BG1 (130)†	2261	0·42	1·50
	56 DD2 (70)	3436	0·45	2·12	15 BE4 (135)	2393	0·44	1·51
	55 ED2 (72)	3222	0·44	2·03	15 BM3 (137)	2006	0·43	1·30
	56 DF1 (78)	2979	0·44	1·90	15 BG4 (144)	2043	0·43	1·32
	56 DC1 (79)	3296	0·44	2·10	15 BM4 (147)	2108	0·43	1·35
log. average life		3258	—	—	—	2157	—	—
		(3·5129)	average 2·08			(3·3339)	average 1·40	
std. dev. of log life		0·0241	—	—	—	0·0320	—	—
Coeff. variation		0·0069	—	—	—	0·0096	—	—
3	55 DA2 (65)†	7188	0·56	3·58	15 BJ3 (134)†	4294	0·52	2·28
	55 DB2 (67)	8215	0·56	4·07	15 BL1 (140)	4661	0·54	2·38
	55 EB2 (71)	8580	0·55	4·30	15 BJ2 (143)	4681	0·55	2·38
	56 DF2 (74)	6637	0·56	3·28	15 BL4 (146)	4757	0·55	2·39
	56 DA1 (77)	7041	0·52	3·78	15 BE2 (149)	5475	0·56	2·74
log. average life		7497	—	—	—	4759	—	—
		(3·8749)	average 3·80			(3·6775)	average 2·43	
std. dev. of log. life		0·0471	—	—	—	0·0382	—	—
Coeff. variation		0·0122	—	—	—	0·0104	—	—
2	55 EC1 (64)	24 764	0·75	9·15	15 BK4 (132)	9746	0·71	3·81
	55 DD2 (66)†	25 036	0·73	9·48	15 BL2 (139)	12 248	0·71	4·77
	55 EG2 (68)	57 139	0·75	21·12	15 BK3 (141)	11 142	0·72	4·31
	55 DE1 (69)	23 561	0·75	8·72	15 BM1 (145)†	12 163	0·73	4·63
	56 DE2 (76)	21 791	0·73	8·29	15 BD3 (148)	12 388	0·73	4·70
log. average life		28 311	—	—	—	11 492	—	—
		(4·4520)	average 11·37			(4·0604)	average 4·44	
std. dev. of log. life		0·1721	—	—	—	0·0440	—	—
Coeff. variation		0·0387	—	—	—	0·0108	—	—
1	56 DB2 (75)	760 340*	1·01	209·53	15 BM2 (129)	30 628	0·98	8·64
	56 DE2 (80)	696 624*	1·05	184·70	15 BL3 (131)†	24 813	0·97	7·08
	56 DB1 (81)†	448 389	1·05	118·44	15 CA1 (133)	27 350	1·14	6·66
	56 DC2 (82)	718 000*	1·06	188·91	15 BD2 (138)	38 912	0·99	10·95
	55 DE2 (83)	717 000*	1·06	187·21	15 BJ4 (142)	28 469	0·98	8·07
log. average life		656 842	—	—	—	29 679	—	—
		(5·8175)	average 177·76			(4·4724)	average 8·28	
std. dev. of log. life		0·0937	—	—	—	0·0736	—	—
Coeff. variation		0·0161	—	—	—	0·0165	—	—

* Runout specimens.

† Examined in scanning electron microscope.

Table 6 indicates the basic information derived from counting the "program" markings on the photographs of the fracture surfaces of the 15 specimens tested under program-loading conditions.

TABLE 6
Program Markings

Test Condition	Test no.	Specimen no. EM	Total Life (Programs)	No. of "Program" Bands†	Initiation Life (Programs)
Dry Air, Standard Program	38*	55 DC2	47	19	28
	39*	55 DF2	44	21	23
	40*	55 DA1	41	18	23
	52*	55 EC2	45	20	25
	53*	55 EF2	52	22	30
	154*	15 BG2	48	22	26
	log. average		46	20	26
Dry Air, Truncated Program	153	15 BF4	31	18	13
	155	15 BG3	29	10–14	19–15
	log. average		30	15	15
Wet Air, Standard Program	55*	55 EB1	18	6‡	12
	56*	55 ED1	16	6	10
	58	55 EE1	20	6	14
	61*	55 DF1	17	6	11
	84	55 EF1	15	6	9
	150*	15 BD1	17	6	11
	log. average		17	6	11
Wet air, Truncated Program	152	15 BE2	9	4 min.	5 max.

* Specimens used for determination of crack propagation rates.
† From crack length of 0·1 mm.
‡ Estimated, see Section 2.4.

4. DISCUSSION

Tables 4 and 5 clearly indicate that there are significant differences in the total fatigue lives in the two extreme environmental water vapour conditions used under both the standard and a truncated program-load fatigue sequence, and also for each of the four individual constant-amplitude load ranges. The ratios of the log. average $\frac{\text{"wet" air}}{\text{"dry" air}}$ lives (in cycles) under each condition are given in Table 7.

The constant-amplitude tests indicate an increasingly deleterious effect of environment as the load range is reduced, and this generally supports previous findings (Ref. 6) relating to the simultaneous actions of corrosion and fatigue stressing. Previously reported tests (Ref. 14) on SAE 4340 steel indicated a value of about 0·2 for the ratio of fatigue lives in "wet" and "dry" air under the standard program-load sequence, compared with a value of 0·38 for D6AC in the current investigation. However, in the case of the SAE 4340 tests, each of the corresponding stress ranges was about 15% less than for the D6AC tests; and thus it is not surprising that a greater effect of the "wet" air environment was demonstrated by the SAE 4340 steel.

A comparison of the total lives obtained under the standard and truncated programs shows

TABLE 7

Ratio of $\frac{\text{"wet" air}}{\text{"dry" air}}$ fatigue lives

Program Loading		Constant-amplitude Loading, (Stages)			
Standard Program	Truncated Program	4	3	2	1
0·38	0·31	0·66	0·63	0·41	<0·045

the ratios (truncated/standard) to be 0·63 and 0·51 for the "dry" and "wet" air environments respectively; and demonstrates the beneficial effects on total life of including the two cycles of the highest load range (stage 4) under both environments in this particular loading sequence.

Table 6 indicates that the omission of the two high load cycles in the standard program decreases the *initiation* life by about half in both wet and dry air environments. The results do not indicate whether the omission of these loads causes any significant differences in crack propagation life, although in dry air some slight decrease is indicated. Similarly, no positive evidence of retardation of the crack propagation rate was apparent on the fracture surfaces of standard-program specimens after the application of the two cycles of the highest load range.

It can also be seen from Table 6 that, under the standard program, the *initiation* life in wet air is about half that in dry air, and that the propagation life to failure in wet air is about one-third of that in dry air. This suggests that the environment used had a more significant effect on the crack propagation phase than on the crack initiation phase of the fatigue process.

Crack propagation rates per program (da/dN) were derived from crack length measurements taken on photographs of specimens tested under the standard program in both wet and dry air. Stress intensities at different crack lengths were calculated using Newman's stress analysis for "through" cracks emanating from a circular hole in a rectangular plate (Ref. 7). Because of the limitations which the model imposed, some of the geometries—namely those in which the crack did not extend over the full width of the specimen—were not amenable to this method of analysis. The fractures of six dry, but only four of the six wet environment specimen fractures were suitable for this purpose—see Table 6.

Composite curves (Fig. 6) of da/dN against ΔK for both the dry and wet air results under standard program loading were then determined from the pooled data using linear regression analysis. At all stress intensities up to about 90 MPa.m$^{\frac{1}{2}}$, the crack propagation rate under program-loading in wet air is greater than in dry air. For example, at 60 MPa.m$^{\frac{1}{2}}$ the ratio is about 3:1. These curves exhibit similar relative slopes to those from *constant-amplitude* tests on D6AC steel (Refs 8 and 9) in dry air and distilled water environments respectively. The ratios of the slopes of the crack propagation curves (exponent "n" in the Paris equation) are 2·06 (3·7/1·8) under the current program-loading conditions, and 2·48 (2·53/1·02) for the constant-amplitude data at 1 Hz given in Ref. 9. With the limited amount of data it is not clear whether there is any significance in the differences between these ratios. It should be noted, however, that both of the *program-load* crack propagation curves incorporate average rates over four load ranges, and represent sets of conditions in which crack retardation effects are probably present.

A comparison of the propagation lives in dry air given in Table 6 for specimens tested under the standard and truncated programs (ratio 1·33) indicates that the propagation period is less under the truncated program. The Wheeler model of crack retardation (Ref. 10) and a computer program developed by Keays (Ref. 11) were used to provide a mathematical estimate of the differences in crack propagation lives of these specimens. Details of the numerical values assumed for use in the Wheeler model are given in the Appendix I.

The ratios of the estimated propagation lives (standard/truncated) for various values of the Wheeler retardation exponent "m" are given in Table 8. It is clear from this table that the model predicts longer lives under the standard program, in accordance with the experimental findings.

For the particular test conditions used in the current investigation the value of "m" must be 1·55, in order to achieve correspondence with the experimental life ratio of 1·33. This compares with a value of 1·3 for D6AC steel suggested by Wheeler.

Fatigue life predictions were made using the constant-amplitude fatigue data and the simple Palmgren–Miner linear cumulative damage hypothesis, and these are detailed in Table 9. This shows that, under both "wet" and "dry" air conditions the maximum theoretical fatigue damage is caused by load range 2, and that the two cycles per program of load range 4 cause virtually no damage. However, the distribution of damage under the load spectra adopted is significantly different in the two environments, particularly at the lowest load range. In all cases the predicted lives are less than the actual lives, i.e. under the particular testing conditions employed the predictive method is conservative, and the ratios of predicted/experimental lives are similar for each pair of the standard and truncated programs. The difference in life ratios between standard and truncated programs in wet and dry air respectively reflects the lack of sensitivity in the predictive method to the influence of the small number of cycles of load range 4.

TABLE 8
Calculation of Retardation Effect

Wheeler Crack Retardation Exponent (m)	Ratio of Crack Propagation Lives $\frac{\text{Standard Spectrum}}{\text{Truncated Spectrum}}$ in Dry Air
1·1	1·12
1·3	1·18
1·5	1·30
1·7	1·46
1·9	1·75

Note: Using a Paris exponent 'n' of 2·55 (Ref. 8).

Fig. 7 compares the current constant-amplitude fatigue data on specimens tested under a "dry" environment with the results of tests on notched D6AC steel specimens of similar U.T.S. and K_t values obtained under axial loading at $R = +0{\cdot}1$ (Ref. 12). Details relating to these other tests are given in Appendix II. The fatigue lives of the current tests are significantly lower than those reported elsewhere. For example, differences in mean lives of about 2:1 at 800 MPa and 4:1 at 600 MPa are indicated, together with a difference of at least 20% in the average fatigue limits. These differences may result from material variations—manufacture and heat treatment; different procedures used in the machining of the stress concentrators; "shape of stress concentrator" effects—keyhole notch versus V-groove circumferential; or differences in the fatigue testing procedures—R values, cyclic frequencies and atmospheric environment. Although it is not possible to assess the relative importance of these variables in comparing the two sets of data, the differences in fatigue lives indicate the need for caution in selecting fatigue data for design and life estimation analyses.

It is of interest to note the very low scatter in fatigue lives of the constant-amplitude data, the average standard deviation of log. life for the "dry" and "wet" environments being 0·081 and 0·047 respectively. However, at all load ranges the product of $S_{max} \times K_t$ either exceeds or is close to the proof stress of the material, and this provides further support for the proposal (Ref. 13) that scatter is minimized when the above product exceeds the yield stress.

TABLE 9

Predicted Fatigue Damage per Program and Predicted Fatigue Lives

Load Range	n	N (log. mean)	$\frac{n}{N}$ Damage per Program	Damage (%)
"*Dry*" *Air*—Standard Program				
4	2	3258	0·00061	1·03
3	128	7497	0·01707	28·72
2	1124	28 311	0·03970	66·80
1	1340	>656 842	<0·00204	<3·43
		$\sum \frac{n}{N} = <0{\cdot}05943$		
		Predicted life = >16·83 programs		
		Ratio predicted/experimental = 0·36		
"*Dry*" *Air*—Truncated Program				
4	—	—	—	—
3	128	7497	0·01707	29·02
2	1124	28 311	0·03970	67·49
1	1342	>656 842	<0·00204	<3·47
		$\sum \frac{n}{N} = <0{\cdot}05882$		
		Predicted life = >17·00 programs		
		Ratio predicted/experimental = 0·58		
"*Wet*" *Air*—Standard Program				
4	2	2157	0·00093	0·54
3	128	4759	0·02690	15·75
2	1124	11 492	0·09781	57·27
1	1340	29 679	0·04515	26·44
		$\sum \frac{n}{N} = 0{\cdot}17078$		
		Predicted life = 5·86 programs		
		Ratio predicted/experimental = 0·33		
"*Wet*" *Air*—Truncated Program				
4	—	—	—	—
3	128	4759	0·02690	15·83
2	1124	11 492	0·09781	57·56
1	1342	29 679	0·04522	26·61
		$\sum \frac{n}{N} = 0{\cdot}16992$		
		Predicted life = 5·89 programs		
		Ratio predicted/experimental = 0·65		

5. CONCLUSIONS

1. Under the four-load-range (standard) program loading sequence used in this investigation, the total fatigue lives in a fully water-saturated air environment were about 35% of those in very dry air.
2. Constant-amplitude tests indicated an increasingly deleterious effect of the wet air environment as the load range was reduced, the ratio of wet air/dry air total fatigue lives ranging from 0·66 at the highest alternating stress (S_{max} = 1000 MPa) to less than 0·045 at the lowest alternating stress (S_{max} = 450 MPa).
3. The omission of the two highest-load-range cycles in each program of 2594 cycles in the sequence (truncation) reduced the *total* fatigue lives by about 40% and 50% respectively in the wet and dry air environments.
4. In wet air, the crack initiation life under the standard program was about half that in dry air, and the propagation life to failure about one-third of that in dry air. The average crack propagation rate in wet air was up to three times faster than that in dry air. This indicates that the environment has a greater effect on the crack propagation phase than on the crack initiation phase of the fatigue process.
5. The relative slopes of the fatigue crack propagation curves (da/dN vs ΔK) in both the dry and saturated air environments under *standard program loading* were similar to those reported elsewhere for *constant-amplitude* tests in dry air and distilled water respectively.
6. In accordance with the experimental findings, the Wheeler model of crack retardation predicted an increase in fatigue life in the standard, compared with the truncated program. However, for the model to predict the experimentally determined retardation, a value of 1·55 was required for the retardation exponent compared with 1·3 suggested by Wheeler.
7. For both wet and dry atmospheres, the lives predicted using the Palmgren–Miner linear cumulative damage hypothesis were less than the actual lives; the ratio predicted/actual was about 0·36 for dry air and 0·33 for wet air conditions. Thus, under the particular load sequences and environments used, the predictive method was conservative.

REFERENCES

1. Spitzig, W. A. and Wei, R. P. Fatigue crack propagation in modified 300-grade maraging steel. *Engng Fract. Mech.*, vol. 1, April 1970, pp. 719–726.
2. Li Che-yu, Talda, P. M. and Wei, R. P. The effect of environments on fatigue crack propagation in an ultra-high strength steel. *Int. J. Fract. Mech.*, vol. 3, no. 1, March 1967, pp. 29–36.
3. Neu, C. E. and Fletcher, A. R. Fatigue crack growth behaviour of four high strength steels in two humid environments, Part I. *Rep. Nav. Air Develop. Cent.* no. NADC-MA-7060, Jan. 29, 1971.
4. Lee, H. H. and Uhlig, H. H. Corrosion fatigue of type 4140 high strength steel. *Metallurg. Trans.*, vol. 3, no. 11, Nov. 1972, pp. 2949–2957.
5. Mann, J. Y. and Kemsley, D. S. Effects of corrodents on the fatigue life of an ultra-high strength steel. *Effects of chemical environment on fracture processes.* [Editors: C. J. Osborn and R. C. Gifkins.] Melbourne, University of Melbourne, 1974, pp. 207–220.
6. Marsh, K. J., Martin, T. and McGregor, J. The effect of random loading and corrosive environment on the fatigue strength of fillet-welded lap joints. *Rep. Natl Engng Lab.* no. 587, Feb. 1975.
7. Newman, J. C. An improved method of collocation for the stress analysis of cracked plates with various shaped boundaries. *Natl Aero. Space Admin.* TN D-6376, Aug. 1971.
8. Paris, P. C., Bucci, R. J. and Little, C. D. Fatigue crack propagation of D6AC steel in air and distilled water. *Stress analysis and growth of cracks.* ASTM STP no. 513, 1972, pp. 196–217.
9. Ryan, N. E. Fatigue crack growth and fracture in D6AC steel. *Aircraft structural fatigue. Rep. Aeronaut. Res. Labs.* no. ARL/STRUCTURES 363—MATERIALS 104, Aug. 1977, pp. 393–418.
10. Wheeler, O. E. Spectrum loading and crack growth. *Trans. Am. Soc. mech. Engrs* (*J. Basic Engng*), vol. 94, no. 1, March 1972, pp. 181–186.
11. Keays, R. H. Numerical evaluation of Wheeler's model of fatigue crack propagation for programmed load spectra. *Note Aeronaut. Res. Labs* no. ARL/SM. 376, April 1972.
12. General Dynamics Corporation. Steel alloy selection for F-111, justification data for D6AC steel. *General Dynamics/Fort Worth Rep.* no. FZM-12-408, Feb. 5, 1964.
13. Mann, J. Y. Some phenomenological aspects of scatter in fatigue. *Rep. Aeronaut. Res. Labs* no. ARL/SM. 342, Nov. 1972.
14. Kemsley, D. S. The influence of the water vapour content and the temperature of an air environment on the fatigue behaviour of SAE 4340 steel. *Aircraft structural fatigue. Rep. Aeronaut. Res. Labs* no. ARL/STRUCTURES 363—MATERIALS 104, Aug. 1977, pp. 459–477.

APPENDIX I—NUMERICAL VALUES USED IN WHEELER MODEL ANALYSIS

Paris Law for Crack Propagation

$$\frac{da}{dN} = C(\Delta K)^n$$

Wheeler Model

$$\frac{da}{dN} = C_p . C . (\Delta K)^n$$

where:

$$C_p = \left(\frac{r_y}{a_p - a}\right)^m \quad \text{when } a + r_y < a_p$$

$$C_p = 1 \quad \text{when } a + r_y \geqslant a_p$$

(r_y denotes the current yield zone; $a_p - a$ is the distance from the crack tip to the edge of the previous yield zone; m is a shaping exponent; n is the slope of the Paris crack propagation relationship, and C is a constant.)

$$r_y = \frac{1}{\alpha} . \frac{K^2}{\sigma_y^2}$$

where: K = fracture toughness
σ_y = material yield strength
α = a parameter.

(i) *Material Constants*

Paris Law constant	$C = 2 \times 10^{-9}$
Paris Law exponent	$n = 2 \cdot 55$ (Ref. 8)
Material yield strength	$\sigma_y = 1\,380$ MPa (200 ksi)
Plane strain fracture toughness	$K_{IC} = 90$ ksi in.$^{\frac{1}{2}}$

(ii) *Specimen Constant*

Test section area	= 58 mm^2 (0·09 in.^{2})

(iii) *Wheeler Model Values*

Initial crack half length	$a_0 = 0 \cdot 025$ mm (0·001 inch)
Maximum limit of crack half length	$a_{max} = 10 \cdot 15$ mm (0·400 inch)
Plastic zone size parameter (plane strain)	$\alpha = 6\pi$
Retardation exponent	m = see Table 8.

Because the computer program developed by Keays (Ref. 11) was based on the use of Imperial Units rather than S.I. units, the former were used in the numerical analysis. The Paris Law constant C thus relates to "a" in inches, σ in ksi, and K_{IC} in ksi. in$^{\frac{1}{2}}$.

APPENDIX II—DATA RELATING TO OTHER D6AC STEEL FATIGUE TESTS [REF. 12] SHOWN ON FIG. 7

Material Form	Die forging
Specimen Direction	Longitudinal
Heat Treatment	Austenitize 900°C, transfer to furnace at 510°C and hold. Quench into salt at 190°C or oil at 60°C, air cool. Stress relieve 190° to 288°C. Double temper (552°C) for two hours to required strength level.
Ultimate Tensile Strength	1520 to 1650 MPa (220 000 to 240 000 psi)
Type of Specimen	Circular section (6·4 mm or 7·6 mm). 60° circumferential V-groove, root radius 0·3 mm or 0·4 mm, $K_t = 3$
Loading Conditions	Axial loading, $R = +0 \cdot 1$
Cyclic Frequency	Not stated
Environment	Not stated

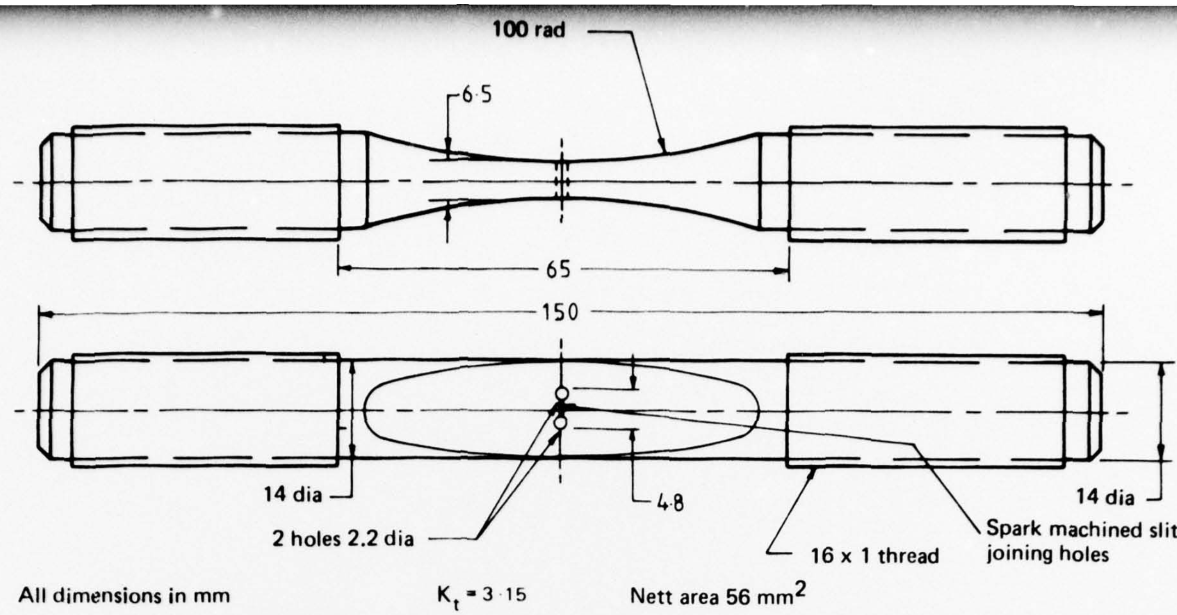


FIG. 1 KEYHOLE – NOTCHED (K_t = 3.15) FATIGUE TEST SPECIMEN

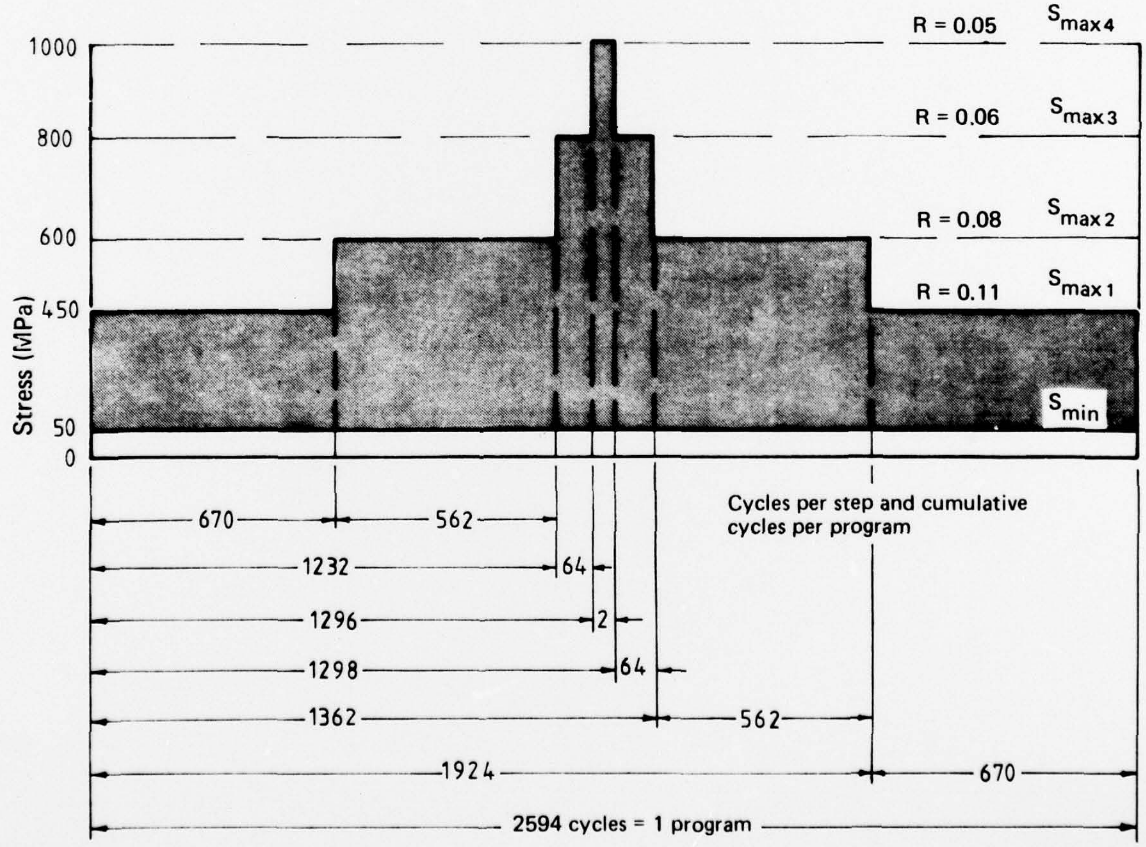


FIG. 2 FOUR-LOAD-RANGE PROGRAM LOADING SEQUENCE

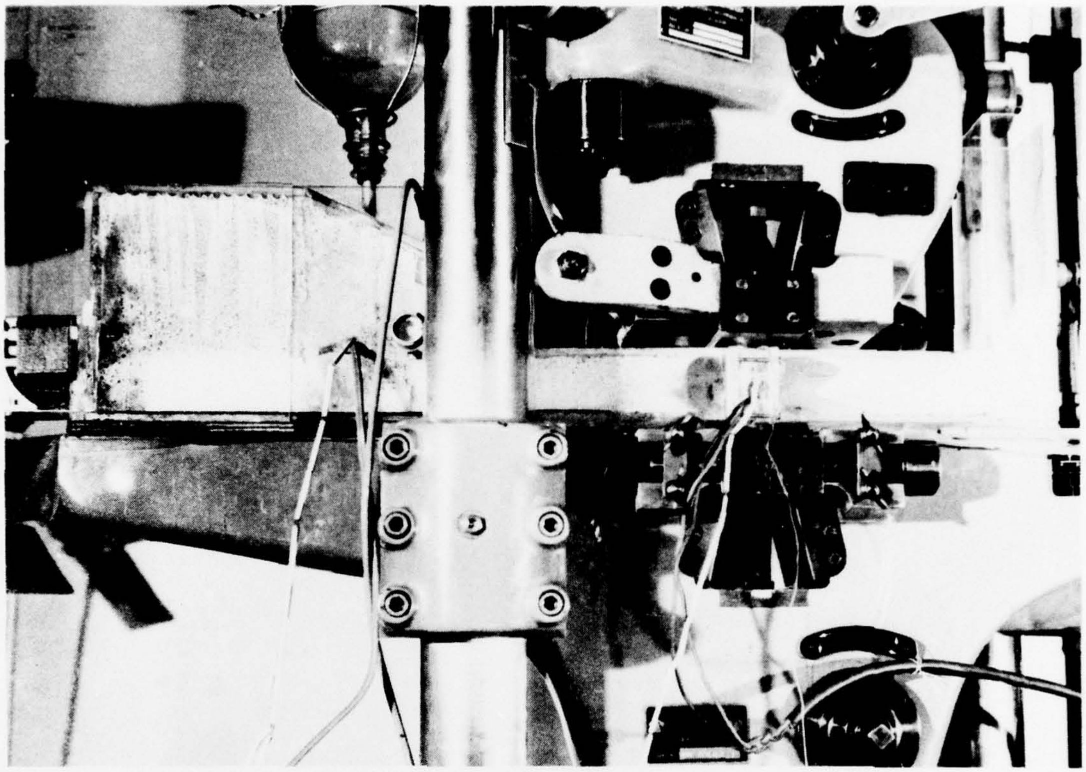


FIG. 3 ENVIRONMENTAL CHAMBER

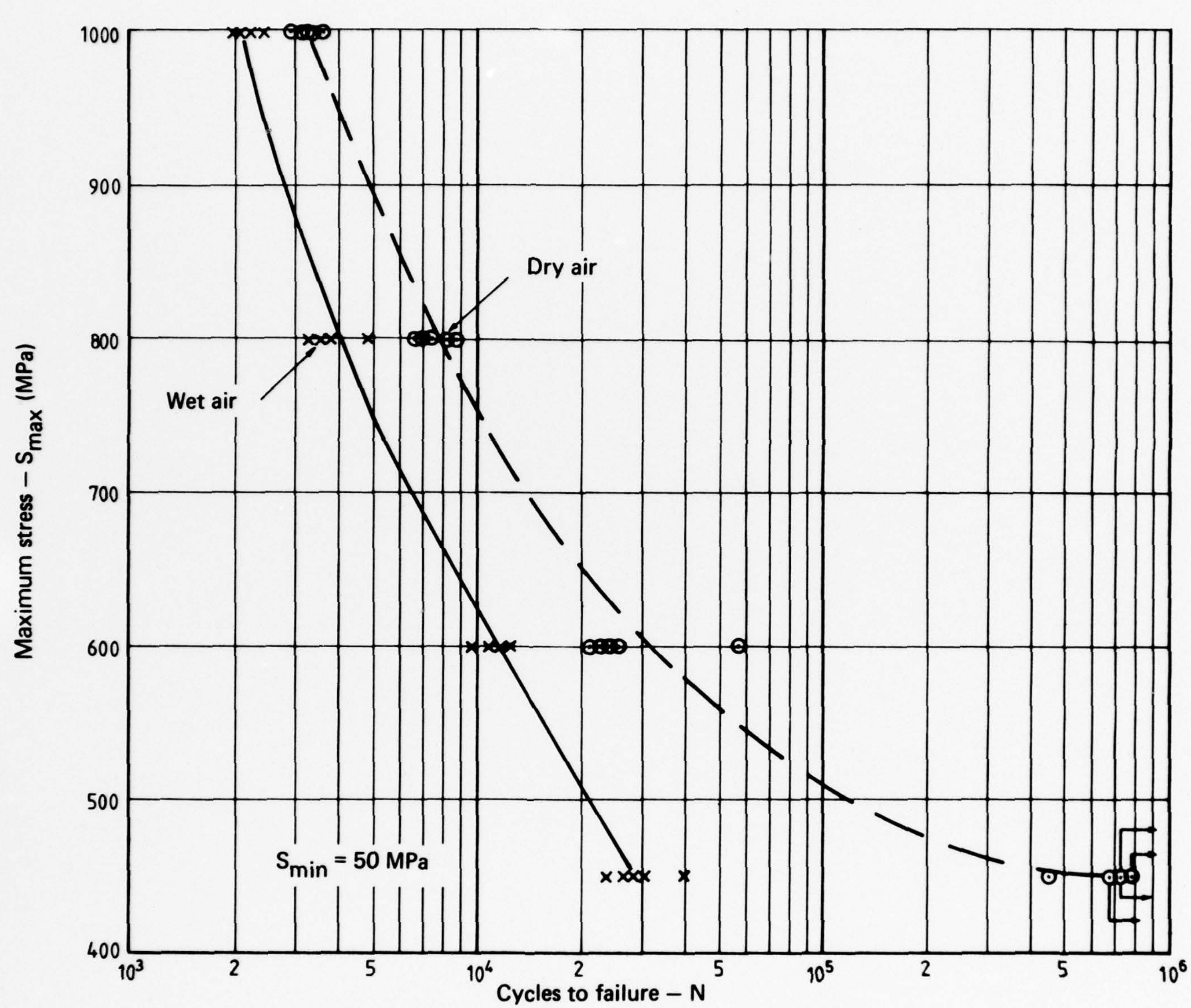
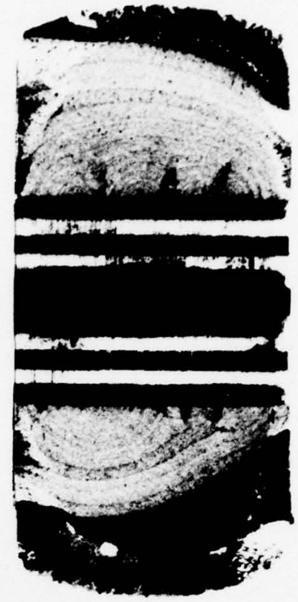
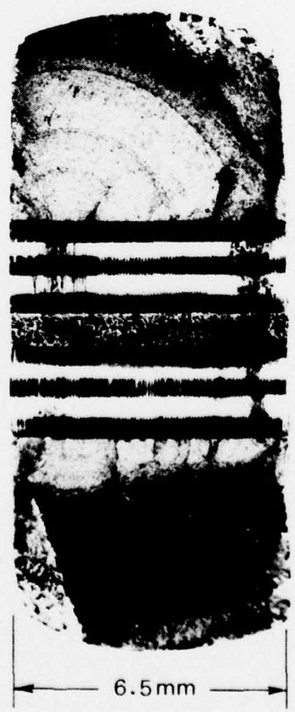


FIG. 4 CONSTANT – AMPLITUDE TEST RESULTS

(a) Dry air standard program
Spec. no. EM 55 DF 2



(b) Dry air truncated program
Spec. no. EM 15 BG 3



(c) Wet air standard program
Spec. no. EM 55 ED 1

FIG. 5 FRACTURE SURFACES

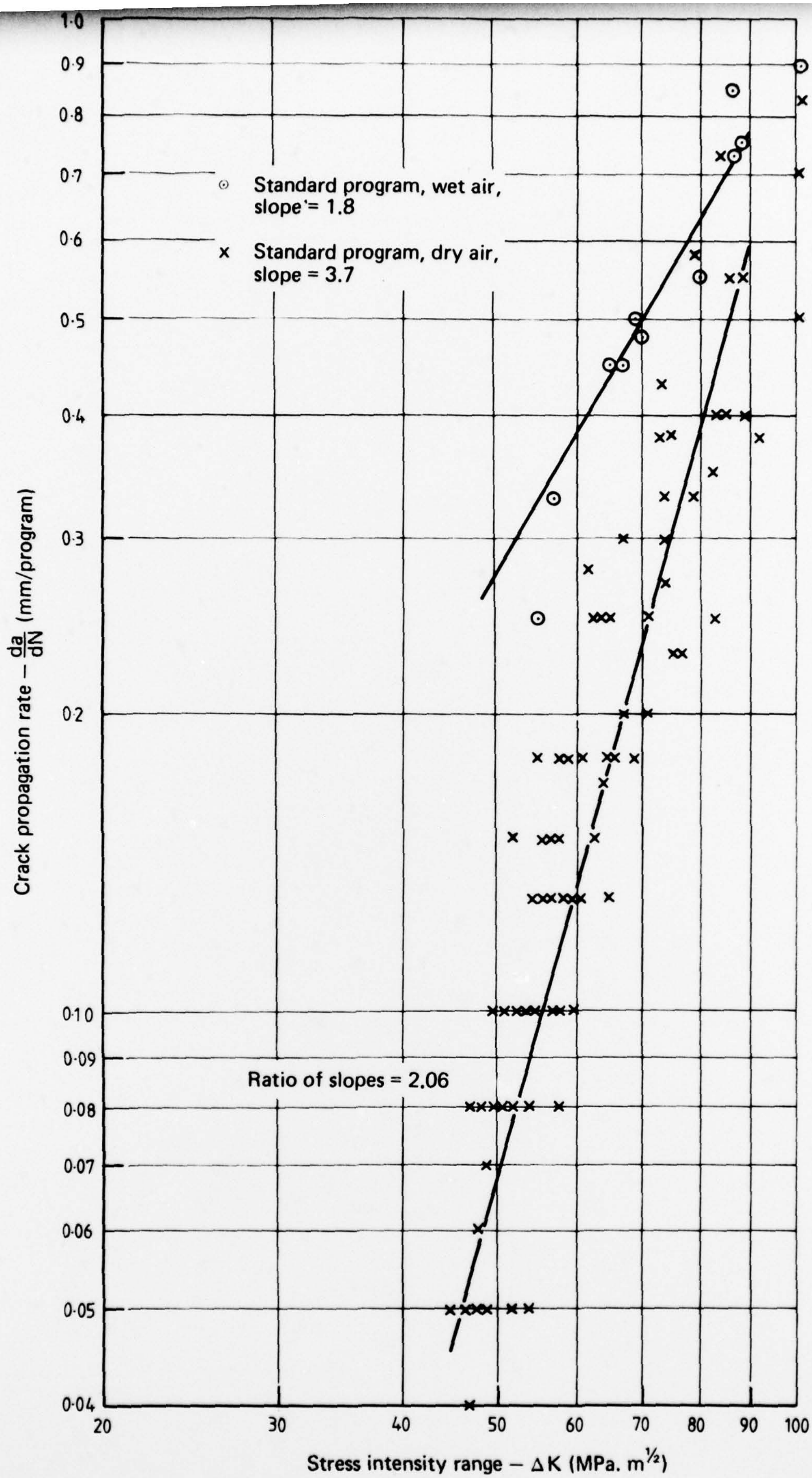


FIG. 6 CRACK PROPAGATION RATES

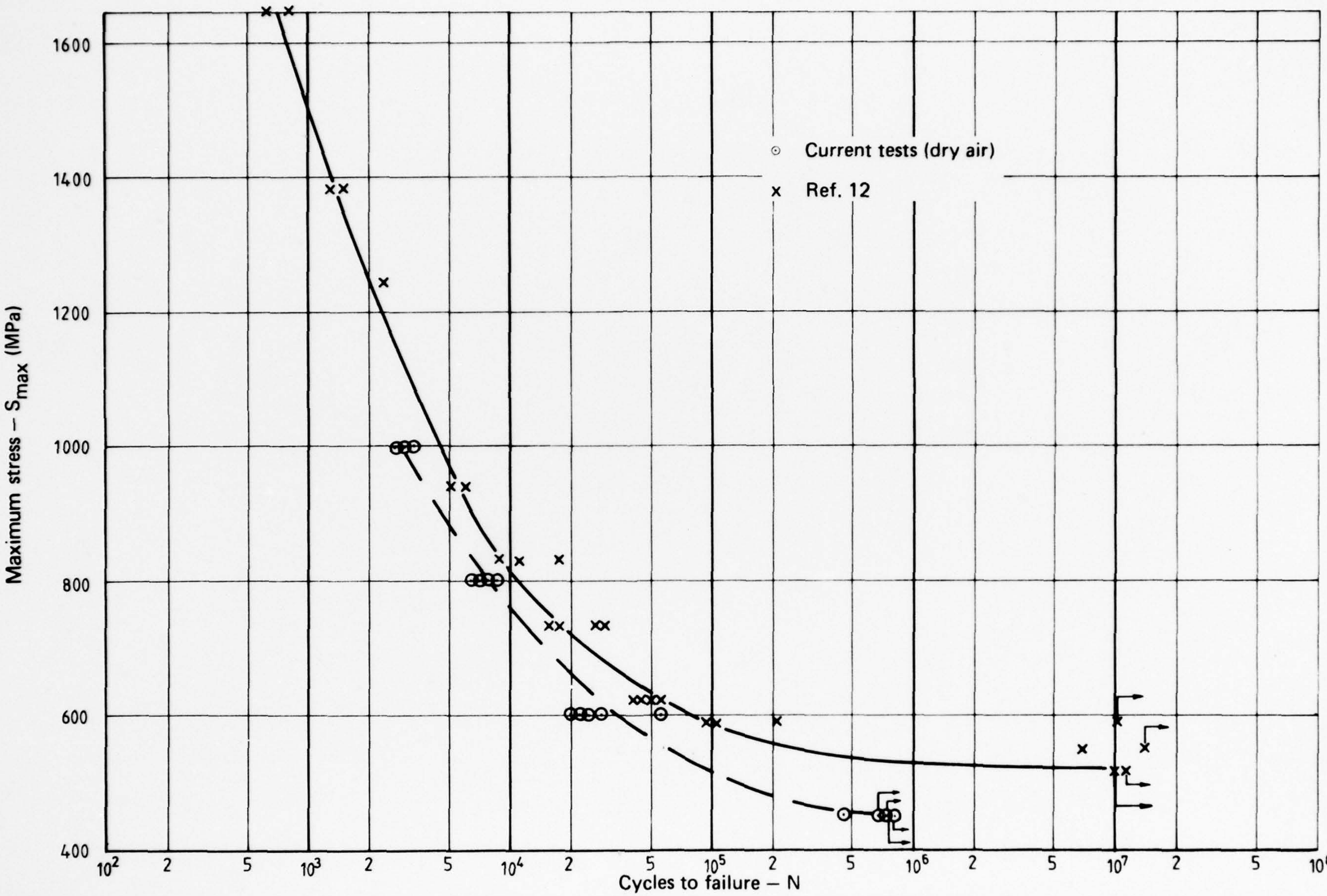


FIG. 7 AXIAL LOAD FATIGUE DATA D6AC STEEL, $K_t \simeq 3$

DISTRIBUTION

	Copy No.
AUSTRALIA	
Central Office	
Chief Defence Scientist	1
Executive Controller, ADSS	2
Superintendent, Defence Science Administration	3
Defence Library	4
J.I.O.	5
Assistant Secretary, DISB	6–21
Aeronautical Research Laboratories	
Chief Superintendent	22
Superintendent, Structures Division	23
Structures Divisional File	24
Authors— J. Y. Mann	25
— D. S. Kemsley	26
J. M. Finney	27
G. S. Jost	28
D. G. Ford	29
Superintendent, Materials Division	30
N. E. Ryan	31
Materials Research Laboratories	
Library	32
Weapons Research Establishment	
Library	33
Central Studies Establishment	
Library	34
Engineering Development Establishment	
Library	35
RAN Research Laboratory	
Library	36
Navy Office	
Naval Scientific Adviser	37
Army Office	
Army Scientific Adviser	38
Royal Military College	39
US Army Standardisation Group	40
Air Force Office	
Air Force Scientific Adviser	41
Aircraft Research and Development Unit	42
Engineering (CAFTS) Library	43
D.Air Eng.	44
H.Q. Support Command (SENGSO)	45

DEPARTMENT OF PRODUCTIVITY

Government Aircraft Factories

Library	46

DEPARTMENT OF TRANSPORT

Director-General Library	47
Airworthiness Group (Mr. R. Ferrari)	48

STATUTORY, STATE AUTHORITIES AND INDUSTRY

Australian Atomic Energy Commission (Director) NSW	49
C.S.I.R.O. Central Library	50
C.S.I.R.O. Mechanical Engineering Division (Chief)	51
Qantas, Mascot, NSW	52
Trans-Australia Airlines, Library	53
Ansett Airlines of Australia	54
Australian Paper Manufacturers (Dr. Norman)	55
BHP Central Research Laboratories	56
BHP Melbourne Research Laboratories	57
Commonwealth Aircraft Corporation (Manager)	58
Commonwealth Aircraft Corporation (Manager of Engineering)	59
Hawker de Havilland Pty. Ltd. (Librarian) Bankstown	60

UNIVERSITIES AND COLLEGES

Adelaide	Barr Smith Library	61
Australian National	Library	62
Flinders	Library	63
James Cook	Library	64
Melbourne	Engineering Library	65
Monash	Library	66
	Professor I. J. Polmear, Materials Engineering	67
Newcastle	Library	68
New England	Library	69
New South Wales	Physical Sciences Library	70
Queensland	Library	71
Tasmania	Engineering Library	72
Western Australia	Library	73
RMIT	Library	74
	Mr. H. Millicer, Aeronautical Engineering	75

CANADA

CAARC Co-ordinator Structures	76
Energy, Mines and Resources Dept. Physics and Metallurgy Research Laboratories (Dr. A. Williams)	77
NRC, National Aeronautics Establishment, Library	78

UNIVERSITIES

McGill Library	79
Toronto Institute of Aerophysics	80

FRANCE

AGARD, Library	81
ONERA, Library	82
Service de Documentation, Technique de L'Aeronautique	83

Royal Armament Research and Development Est., Library	113
CATC Secretariat	114
Aircraft and Armament Experiment Establishment	115
Military Vehicles Engineering and Experimental Est.	116
Admiralty Materials Laboratories (Dr. R. G. Watson)	117
National Engineering Laboratories (Superintendent)	118
National Gas Turbine Establishment (Director)	119
National Physical Laboratories Aero. Division (Superintendent)	120
British Library, Science Reference Library	121
British Library, Lending Division	122
Naval Construction Research Establishment (Superintendent)	123
CAARC Co-ordinator, Structures	124
Aircraft Research Association, Library	125
British Non-ferrous Metals Association	126
British Ship Research Association	127
C. A. Parsons, Library	128
Central Electricity Generating Board	129
Fulmer Research Institute Ltd. (Research Director)	130
Motor Industries Research Association (Director)	131
Science Museum Library	132
Welding Institute, Library	133
Hawker Siddeley Aviation Ltd., Brough	134
Hawker Siddeley Aviation Ltd., Greengate	135
Hawker Siddeley Aviation Ltd., Kingston-upon-Thames	136
Hawker Siddeley Dynamics Ltd., Hatfield	137
British Aircraft Corporation (Holdings) Ltd., Military Aircraft	138
British Aircraft Corporation (Holdings) Ltd., Commercial Aviat. Divn.	139
British Hovercraft Corporation Ltd. (E. Cowes)	140
Fairey Engineering Ltd., Hydraulic Division	141
Short Brothers and Harland	142
Westland Helicopters Ltd.	143

UNIVERSITIES AND COLLEGES

Bristol	Library, Engineering Dept.	144
Cambridge	Library, Engineering Dept.	145
Nottingham	Library	146
Southampton	Library	147
Strathclyde	Library	148
Cranfield Institute of Technology	Library	149
Imperial College	The Head	150

UNITED STATES OF AMERICA

Counsellor Defence Science	151
N.A.S.A. Scientific and Technical Information Facility	152
American Institute of Aeronautics and Astronautics	153
Applied Mechanics Reviews	154
The John Crerar Library	155
The Chemical Abstracts Service	156
Boeing Co. Head Office	157
Boeing Co. Industrial Production Division	158
Cessna Aircraft Co. (Mr. D. W. Mallonee, Executive Engineer)	159
Lockheed Aircraft Co. (Director)	160
Metals Abstracts	161
McDonnell Douglas Corporation (Director)	162